Brazilian Journal of Chemical Engineering

ISSN 0104-6632
Printed in Brazil
www.abeq.org.br/bjche

Vol. 33, No. 03, pp. 617 - 626, July - September, 2016
dx.doi.org/10.1590/0104-6632.20160333s20150143

THE IMPACT OF RADIATION IN THE GAS COMBUSTION MODEL FOR SUGARCANE BAGASSE GRATE BOILER

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(Submitted: March 6, 2015 ; Revised: August 2, 2015 ; Accepted: September 19, 2015)

Abstract - This work evaluates the impact of different radiation models on the results of Computational Fluid Dynamics (CFD) simulation of a sugarcane bagasse grate boiler. CFD has been applied extensively in the development of comprehensive models for biomass heterogeneous combustion. The model presented in this paper considers the turbulent flow represented by the standard k-ε model and the homogeneous combustion of the volatiles CH_4 and CO by the Eddy Dissipation Model (EDM). Thermal profiles have been evaluated by comparing the results obtained without radiation with the results obtained with radiation represented by the P_1 Approximation Method and by the Discrete Transfer Method (DTM). The discussion of the flue gas temperature and chemical composition profiles provides useful information regarding the characteristics of the internal flow and of the equipment operating conditions.
Keywords: Bagasse boiler; Combustion modeling; Radiation; Simulation; CFD.

INTRODUCTION

The operation of a sugarcane bagasse grate boiler requires the knowledge of a large amount of complex simultaneous processes. The most important one is the bagasse heterogeneous combustion under turbulent flue gas flow. Among many strategies applied to model heterogeneous combustion of solid fuels such as coal or biomass, one promising technique involves the use of comprehensive models. The works of Hill and Smoot (1993), Smoot (1997) and Eaton *et al*. (1999) discuss the definitions and develop some important comprehensive models. The comprehensive model approach allows the selection of specific physical processes coupled with mass, momentum and/or energy conservation equations.

Among the physical processes, the flow motion is mathematically described by Navier-Stokes equations that can be solved numerically by Computational Fluid Dynamics (CFD). With respect to the heat transfer mechanisms, the radiation can be considered to be the dominant heat transfer mechanism

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This is an extended version of the work presented at the 20th Brazilian Congress of Chemical Engineering, COBEQ-2014, Florianópolis, Brazil.

in boilers and furnaces operating under high temperatures, which will then influence the fluid flow within the equipment. Therefore, almost all operational variables and physical processes that take place in a grate boiler are affected by the flue gas flow and its temperature profile.

Heat transfer by conduction and convection mechanisms are first-order dependent on the temperature difference. In the radiation mechanism, this dependence is proportional to the difference elevated to the fourth power. Therefore, radiation is the dominant mechanism of energy transfer in nuclear reactors and combustion equipment like furnaces, turbines, engines, combustion chambers, etc. (Mbiock and Weber, 2000). According to Versteeg and Malalasekera (2007) and Siegel and Howell (1992), at higher temperatures (above 1,000 K) radiation is the main heat transfer mechanism. Sosa-Arnao *et al.* (2006) estimate through qualified balances that the Brazilian bagasse boilers reach 793 K to produce steam with 6.57 MPa (gauge pressure), with flame temperatures above 920 K. Hence, the accurate prediction of the heat transferred by radiation is a very important task in the design and operation of combustion chambers (Carvalho and Farias, 1998).

In the present work, CFD comprehensive models are presented to evaluate the impact of radiative heat transfer in a sugarcane bagasse grate boiler. The heterogeneous combustion of sugarcane bagasse is simulated by considering radiation heat transfer represented by two models, namely the Approximation P_1 and the Discrete Transfer Method (DTM). Heterogeneous combustion here means solid particles with different phases of combustion with the fluid surrounding the particle. The model considered the turbulent flow represented by the standard k-ε model and the homogeneous combustion of the volatiles CH_4 and CO by the Eddy Dissipation Model (EDM).

The development of the model was conducted in the progressive way followed by tests performed in several boilers. At first, the gas flow module developed in Ferreira *et al.* (2010) it was implemented. Then a second module covering the spray and sprinkle of liquid and solid fuels was tested. The second module considered two-way and four-way particle interactions as shown by Ferreira *et al*. (2011) and Sosa-Arnao *et al*. (2015). After the completion of these modules, several other phenomena were studied to be incorporated in the model to properly address the heterogeneous combustion process. The wall thermal source effect without combustion or radiation is presented in Ferreira *et al*. (2012), the combustion effect in the boiler is presented in Park *et al.* (2013), thermal radiation is detailed in the present work, and the modeling of all the boiler ancillary parts, including fuel feed and burners, gas and particle flows in boiler tube banks, superheaters, grate windboxes, furnace, and heaters, is presented in Ferreira *et al.* (2015).

METHODOLOGY

Thermodynamic analysis provides satisfactory and reliable results even when a “black box” approach is used for estimation of operating variables. However, monitoring of what happens inside the equipment may be needed to improve a process. As a result, expensive measurement techniques may be required in order to deal with extreme conditions. An alternative to the assessment of what happens inside the boiler is the use of CFD. Through numerical simulations realized inside a computational domain that represents the geometry of interest, a series of phenomena can be estimated. Fluid flow, heat transfer, mixing of gaseous components, chemical reactions and particulate material drag are some of these phenomena simulated.

Considering the processes involved in the operation of a bagasse boiler and their interconnection, the influence of each process on the other is very difficult to assess. In order to tackle this problem, comprehensive models have been used to represent boiler operation as shown in Eaton *et al*. (1999). Following this lead, the present study also developed numerical simulations of the grate sugarcane bagasse boiler using a comprehensive CFD model.

Table 1 shows a generic transport equation and its common features used in the Comprehensive CFD model. The other specific equations describing boiler phenomena are also highlighted.

The main processes that occur inside the boiler and that were studied separately are:

- Turbulent flue gas flow;
- Combustion of volatiles;
- Particulate drag;
- Steps of particle burning.

In order to have each process properly simulated by the global model, it is necessary that a consistent description of these processes through mathematical equations be performed. For example, when the study is about confined industrial flows, the turbulence representation given by the standard k-ε model offers good results (Versteeg and Malalasekera, 2007).

Table 1: Main transport equations considered in the comprehensive CFD model to represent the bagasse heterogeneous combustion in the boiler.

	Generic transport equation	
	$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial(\rho u_i\phi)}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial\phi}{\partial x_i}\right)+S_\phi+S_{p\phi}$	(1)
Equation	Expression	
Continuity	$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0$	(2)
Continuity	$\frac{\partial}{\partial t}(\gamma_c\rho_c)+\frac{\partial}{\partial x_j}\left(\gamma_c\rho_c\overline{u_j}\right)=S_{MS,c}+\sum_{d=1}^{N_P}\Gamma_{cd}$	(3)
Momentum	$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_i}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)+\delta_{ij}\lambda\frac{\partial u_i}{\partial x_j}\right]+\rho g_i+S_{mom}$	(4)
Energy	$\frac{\partial(\rho h_{tot})}{\partial t}+\frac{\partial(\rho u_i h_{tot})}{\partial x_i}-\frac{\partial p}{\partial t}=\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}+\frac{\mu_t}{\Pr_t}\frac{\partial h}{\partial x_j}\right)+S_E$	(5)
Species	$\frac{\partial(\rho Y_i)}{\partial t}+\frac{\partial(\rho u_j Y_i)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_{i,eff}\frac{\partial Y_i}{\partial x_j}\right)+S_I$	(6)
Energy and species	$\frac{\partial(\rho h_{tot})}{\partial t}+\frac{\partial(\rho u_j h_{tot})}{\partial x_j}-\frac{\partial p}{\partial t}=\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_{ij}}+\sum_i^N\Gamma_i h_i\frac{\partial Y_i}{\partial x_j}+\frac{\mu_t}{\Pr_t}\frac{\partial h}{\partial x_j}\right)+S_E$	(7)

Even with the presence of regions with a lack of oxygen inside the boiler, the homogenous combustion of fuel gases from pyrolysis is often considered to be dominated by the mass transfer rate, or gas mixing rate. This is a typical situation for the use of combustion models developed for high Damköhler number like the Eddy Dissipation Model (EDM) or Flamelet. The Eddy Dissipation Model is simpler and more robust than Flamelet, because it does not require a clear definition of the input flow rates of fuel and oxidant. Therefore, the present work used the EDM to represent the combustion of volatiles released by sugarcane bagasse particles in the boiler domain due to its applicability in industrial reactive flow and the reduced computational effort required.

To estimate the boundary conditions involving the composition of volatiles released from bagasse particles, proximate and ultimate analysis of bagasse samples from the South-eastern region of Brazil was used. The tests were performed in the chemistry laboratories of the University of Sao Paulo – Campus Ribeirão Preto (USP-RP) and the Instituto de Pesquisas Tecnológicas de São Paulo (IPT). The chemical species considered were CH_4 (representing the set of light hydrocarbons released during volatilization), CO, O_2, CO_2 and H_2O. The chemical mechanism used here is quite simple, composed of two reactions:

$CH_4 + O_2 \rightarrow CO + H_2O$

$CO + O_2 \rightarrow CO_2$.

The representation of the bagasse trajectories inside the furnace by a one-way coupling would be ideal in a CFD simulation, because the particles are very small and dilute in the domain and their effect is minimal on the flow. The dimensions of the boiler (about 10 m) are orders of magnitude larger than the size of the particles (10^{-3} m). However, it is necessary to account for the heat transfer from flue gases to the particles. The heat transfer promotes drying, volatilization and combustion of released volatiles which, in turn, provides heat leading to the flue gases flow. Thus, the two way coupling is necessary to represent the two way energy interaction between continuous and particulate phases. The particle drag is represented by the Schiller-Neumann model that considers the particles to be spherical rigid solids. The bagasse particles do not interact with each other. The size distribution of bagasse particles used in the simulation can be found in Sosa-Arnao (2008).

RADIATION HEAT TRANSFER

There are many mathematical complications in problems involving heat transfer by conduction, convection and radiation occurring simultaneously for complex geometries such as bagasse boilers. Unless it can be considered that conduction and convection have small contributions compared to radiation, it is not usually possible to obtain an analytical solution for this kind of problem. Thus, numerical methods have been used to obtain the temperature distribution, radiation scattered energy distribution and heat fluxes.

According to Siegel and Howell (1992), the energy transport equation can be represented by:

$$\rho c_P \frac{DT}{Dt} = \beta T \frac{DP}{Dt} + \nabla.\left(k\nabla T - \vec{q}_r\right) + q''' + \Phi_d \qquad (8)$$

where $\rho c_P \frac{DT}{Dt}$ is the derivative that considers the transient and convective influences on energy conservation; $\beta T \frac{DP}{Dt}$ is the enthalpy modifications due to transient pressure variations; $\nabla.(k\nabla T - \vec{q}_r)$ is the relationship between the convective and the radioactive heat fluxes inside the same gradient; q''' is the heat generation per unit volume and time; and Φ_d is the viscous dissipation function.

The same expression (8) is represented by the commercial CFD software ANSYS CFX (2009) as:

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial P}{\partial t} + \nabla.\left(\rho \vec{U} h_{tot}\right) = \nabla.\left(\lambda \nabla T\right) + S_E \qquad (9)$$

The thermal radiation flux, the volumetric heat generation and the viscous dissipation function have been grouped into the source term S_E in Equation (9). This strategy of representation is very useful to elaborate comprehensive models because, similar to the influence of two-phase drag models on the momentum conservation equation, the models for combustion and radiation are inserted in the source terms in the energy conservation equation. Therefore, the goal of the radiation modeling is to obtain the source term, S_E.

Although the heat transfer by radiation is a spectral phenomenon in space and time, its contribution to energy conservation is scalar. Thus, the key issue for the non-spectral models represented by S_E is to simplify the radiation as an isotropic heat transfer in the system or, at least, inside each computational cell where it is calculated.

The radiation heat transfer is composed of emission, absorption, reflection and scattering components that are considered in the spectral radiation heat transfer equation (RTE) (Versteeg and Malalasekera, 2007):

$$\frac{dI(\vec{r},\vec{s})}{ds} = \kappa I_b(\vec{r}) - \kappa I(\vec{r},\vec{s}) - \sigma_s I(\vec{r},\vec{s}) + \frac{\sigma_s}{4\pi}\int_{4\pi} I\_(\vec{s}_i)\Phi(\vec{s}_i.\vec{s}\,')d\Omega_i \qquad (10)$$

where $\frac{dI(\vec{r},\vec{s})}{ds}$ is the rate of variation of radiation intensity per path length; $\kappa I_b(\vec{r})$ is the emitted radiant intensity; $\kappa I(\vec{r},\vec{s})$ is the absorbed radiant intensity; $\sigma_s I(\vec{r},\vec{s})$ is the out-scattering radiant intensity; $\frac{\sigma_s}{4\pi}\int_{4\pi} I\_(\vec{s}_i)\Phi(\vec{s}_i.\vec{s}\,')d\Omega_i$ is the in-scattering radiant intensity.

Combining the absorbed and out-scattering terms as a sum and manipulating them to define the simple scattering albedo, the equation becomes:

$$\varpi = \frac{\sigma_s}{\kappa + \sigma_s} \qquad (11)$$

And since

$$\tau = \int_0^s \left(\kappa + \sigma_s\right) ds' \qquad (12)$$

Equation (10) can be re-written as,

$$\frac{dI(\tau,\vec{s})}{d\tau} = -I(\tau,\vec{s}) + (1-\varpi)I_b(\tau) + \frac{\varpi}{4\pi}\int_{4\pi} I_-(\vec{s}_i)\Phi(\vec{s}_i,\vec{s})d\Omega_i \tag{13}$$

As a result, the source function can be defined as the sum of the last two right hand terms of Equation (13).

$$S(\tau,\vec{s}) = (1-\varpi)I_b(\tau) + \frac{\varpi}{4\pi}\int_{4\pi} I_-(\vec{s}_i)\Phi(\vec{s}_i,\vec{s})d\Omega_i \tag{14}$$

Now, Equation (13) can be expressed by:

$$\frac{dI(\tau,\vec{s})}{d\tau} + I(\tau,\vec{s}) = S(\tau,\vec{s}) \tag{15}$$

Because of to the complex integral-differential nature of the RTE, analytical solutions are not current available (except in a few idealized cases) and require numerical methods and modeling. The majority of numerical models provide a set of estimated values and equations for the source function. According to ANSYS CFX (2009) and Modest (2003), P_N models and the Discrete Transfer Method (DTM) are appropriate for representing the radiation inside the boiler because the computational domain does not show high aspect ratio regions and its continuous participant medium is semi-transparent.

P_N Approximation

The P_N method provides an expression for the local divergence of the radiative flux (radiative source term) that is differential in form. The expressions can be directly incorporated into the energy equation in differential form that includes other modes of energy transfer (Siegel and Howell, 1992). The P_N approximation expresses the radiation intensity field $I(\vec{r},\vec{s})$ in terms of a two dimensional generalized Fourier series as:

$$I(\vec{r},\vec{s}) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} I_l^m(\vec{r})Y_l^m(\vec{s}) \tag{16}$$

where $I_l^m(\vec{r})$ are coefficients that are a function of position and $Y_l^m(\vec{s})$ are spherical harmonics (Modest, 2003). The N degree of the method means the highest value for l that is the truncated term, for example, P_1 ($l = 0, 1$) or P_3 ($l = 0, 1, 2, 3$), and, consequently, N is the P-approximation order method used. If the chosen value is 1, the P_1 approximation method for radiative heat transfer is being used with the following truncated series Equation (16):

$$I(\vec{r},\vec{s}) = I_0^0Y_0^0 + I_{-1}^{-1}Y_{-1}^{-1} + I_1^0Y_1^0 + I_1^1Y_1^1 \tag{17}$$

Equation (17) can be associated (Modest, 2003) with Legendre polynomials $P_0^0 = 1$; $P_1^0 = \cos\theta$; $P_1^1 = \sin\theta$.

An adopted simplification establishes a linear representation with a scalar function (a) and a three component vector function ($\vec{b}$).

$$I(\vec{r},\vec{s}) = a(\vec{r}) + \vec{b}(\vec{r}).\vec{s} \tag{18}$$

Solving to obtain the heat flux of radiation as a function of the intensity of the incident radiation, the P_1 approximation provides the following equation:

$$\vec{q}_r = -\frac{1}{3(\kappa-\sigma_s) - A\sigma_s}\nabla I_- \tag{19}$$

Because the method does not present any restriction about isotropic emission, scattering or reflection, it can be considered that the P_N might be able to predict anisotropic heat transfer by radiation; however, it assumes isotropic or direction independent radiation intensity. Furthermore, the method presents significant errors to thin layers with strongly anisotropic intensity distributions in 2D or 3D geometries (Modest, 2003). Higher order P_N approximations (like P_3) can minimize, but cannot correct, this issue. Due to the large computational effort necessary to use P_3 versus a small increment in accuracy compared to the P_1 approximation, the use of the P_1 method is recommended for CFD modeling. In fact, the P_1 method is very common in commercial codes but P_3 is frequently absent. More details about the P_1 approximation method are given in Siegel and Howell (1992) and Modest (2003).

Discrete Transfer Method

The Discrete Transfer Method is similar to the Monte Carlo Method (MCM), which is the most accurate method to represent radiation, but DTM requires less computational effort (Versteeg and Malalasekera, 2007, Siegel and Howell, 1992 and Modest, 2003). While MCM is characterized by extensive use of a random number generator, the DTM uses the consideration of isotropic radiation directions and wavelengths. The DTM is based on the concept of representative rays inside the domain and each ray direction is specified in advance rather than being chosen at random. Those rays are solved only for paths between the two boundary walls rather than partially reflected at the walls and tracked to extinction (Lockwood and Shah, 1981).

The DTM establishes an equal division of hemispheres on the domain surfaces into N parts (N is a user input parameter). According to Versteeg and Malalasekera (2007), this division is made by azimuthal and polar angles, calculated respectively as $\delta\theta = \frac{\pi}{2N_\theta}$ and $\delta\phi = \frac{2\pi}{N_\phi}$.

This angular division expresses the isotropic characteristic of the method. Each hemisphere division is represented by a calculated vector that gives the path of a ray (its course) and the intensity of the radiation emitted, absorbed, scattered and reflected. The source function of Equation (14) is expressed as a function of a sum of averaged intensity $I_{-,ave}(\vec{s}_i)$.

$$S(\tau,\vec{s}) = (1-\varpi) I_b(\tau) + \frac{\varpi}{4\pi}\sum_{i=1}^{N} I_{-,ave}(\vec{s}_i)\Phi(\vec{s}_i,\vec{s})d\Omega \qquad (20)$$

Because the source function is assumed to be constant over the interval, the computational cell radiation intensity is calculated with this average S value. This consideration is another isotropy feature present in DTM. The initial intensity of each ray at its originating surface element is given by:

$$I_0 = \frac{q_+}{\pi} \qquad (21)$$

where

$$q_+ = \varepsilon_s E_s + (1-\varepsilon_s)q_- \quad \text{and} \quad q_- = \sum_N I_-(\vec{s})\vec{s}.\vec{n}d\Omega$$

Unless the surfaces are black, an iterative solution is required because q_+ is function of q_-. With converged values for q_+ and q_- it is possible to obtain the net radiative heat flow out of each surface element area A_i,

$$Q_{si} = A_i(q_+ - q_-) \qquad (22)$$

Thus, after reaching a converged solution to I_- and $I_{-,ave}$, the DTM calculates the radiation source for each medium cell by energy balance.

$$\delta Q_{gk} = \int_{\delta\Omega} (I_{n+1} - I_n) A_i (-\vec{s}_k.\vec{n}) d\Omega_k \qquad (23)$$

The radiative heat flux found from Equation (8) can be obtained by summing the source contributions from all the N rays passing through a cell divided by its volume (Versteeg and Malalasekera, 2007):

$$\nabla\vec{q}_r = \frac{1}{\Delta V}\sum_{k=1}^{N}\delta Q_{gk} \qquad (24)$$

Another good description of DTM can be found in Carvalho and Farias (1998).

SIMULATIONS

The computational domain represents the furnace of a bagasse boiler with primary air supply being fed through a grate with more than 26,000 orifices in the bottom furnace. In the model representation this structure is simplified to 144 inlet plate rectangular surfaces. The lower secondary air is composed of 49 circular air ports next to the furnace bottom in the rear wall. The upper secondary air is composed of 20 rectangular air interlaced ports placed in the front and rear walls above the bagasse injection level. The bagasse is supplied by six swirl burners under alternating rotation direction and it is represented by 12,000 particles in each burner with size distribution estimated from Sosa-Arnao (2008). The outlet is placed before the superheater position. The temperature of the boiler walls is constant at 558 K, estimated in the coal-fired boiler simulated by Butler and Webb (1991) and by the water boiling point measured inside the wall ducts of south eastern Brazilian boilers. Figure 1 shows a general view of the computational domain with its respective boundary conditions. Table 2 presents the boundary conditions used in the simulations.

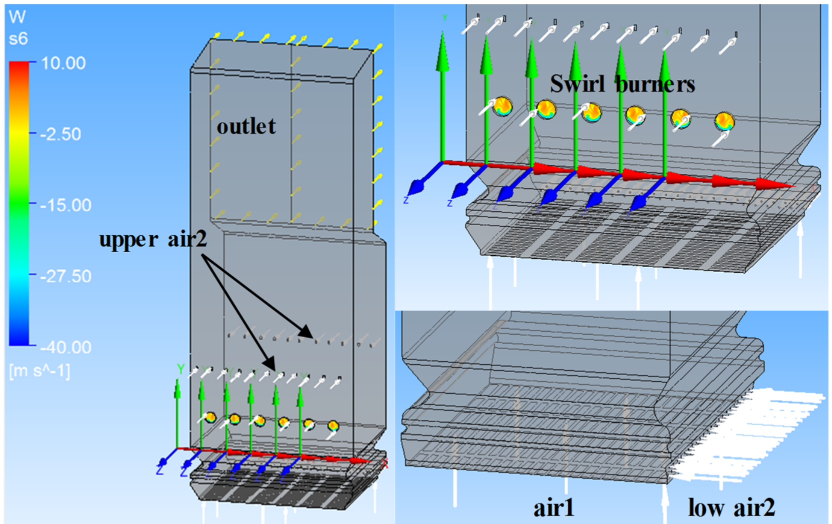


Figure 1: General view of the boundary conditions used in the bagasse boiler simulations.

Table 2: Boundary conditions used in the bagasse boiler simulations.

Inlet				
Name	Mass flow	Temperature	Composition	Obs.
air1	78.00 kg/s	1523 K	0.232 O_2	
air2F	11.19 kg/s	423 K	0.232 O_2	- 15° slope
air2F	11.19 kg/s	423 K	0.232 O_2	- 15° slope
air2G	6.06 kg/s	323 K	0.232 O_2	
swirl	Continuous phase	(imported velocity profiles)		
s1	SNHA	923 K	0.232 O_2	Clockwise
s2 and s4	SNAHF	923 K	0.232 O_2	Anti-Clockwise
s3 and s5	SNHF	923 K	0.232 O_2	Clockwise
s6	SNAHA	923 K	0.232 O_2	Anti-Clockwise
swirl	Disperse phase			
s1 to s6	Nº particles	12,000		
	Mass flow	4.13 kg/s		
	Temperature	423 K		
	Diameters	5.56; 2.83; 1.19; 0.59; 0.297; 0.149; 0.05 [mm]		
	mass fraction	0.0645; 0.0965; 0.1291; 0.316; 0.2585; 0.1125; 0.0229		
Outlet				
Outlet	outlet pressure	-49 Pa (gauge)		
Wall				
Walls	others resting domain surfaces			
Temperature	558 K			
Radiation	Emissivity	0.85		
	Diff. Fraction	1.0		

In this work, sugarcane bagasse is treated as a solid hydrocarbon fuel, for which proximate and ultimate analysis, based on Saidur *et al.* (2011), are presented in Table 3. The bagasse particles undergo drying and volatilization before transforming into char. In this work, the char combustion produces CO_2 for the continuous phase and generates ash particles. Table 4 presents the physical properties of the three solid species of the model. Due to the lack of data in the literature, the char and ash species are the same as the ones considered in a coal combustion case.

Table 3: Proximate and ultimate analysis of sugar-cane bagasse.

Proximate Analysis		Ultimate Analysis	
Species	Mass fraction	Species	Mass fraction
Ash	0.0244	C	0.4759
Moisture	0.0200	H	0.0573
Char	0.1095	O	0.4195
Volatiles	0.8461	N	0.0019
		Cl	0.0004
LHV	6.6 MJ/kg	S	0.0006
Reference (T, P)	298 K; 1 atm	**Saidur *et al.* (2011)**	

Table 4: Physical properties of the solid material used in the simulations.

Property	bagasse	char	ash
Molar mass [kg/kmol]	96.14	12	12
Density [kg/m^3]	492	2000	1000
C_P [J/kg.K]	1760	1600	800
Reference (temperature)	298 K	298 K	285 K

It is expected that the values of the density of char and ash from coal provides inaccurate trajectories because of the strong influence of density in the particle pathways.

It is known that the volatilization releases a large variety of complex organic compounds from biomass degradation products. Some of them are quickly consumed and transformed into combustion products (CO_2, CO, H_2, H_2O, light hydrocarbons and some sulfur compounds). The light hydrocarbons released are represented by CH_4 and sulfur compounds are not considered in this work. The continuous phase, where the homogeneous combustion reactions take place, is defined as a mixture containing the following species: CH_4, CO, CO_2, H_2O, O_2 and N_2 (constraint). The volatilization is represented by a first order chemical reaction with Arrhenius constants obtained from Shanmukharadhya e Sudhakar (2007) as $A = 2.13x10^6$ s^{-1} and E = 92,600 J/mol.

Three cases have been simulated:

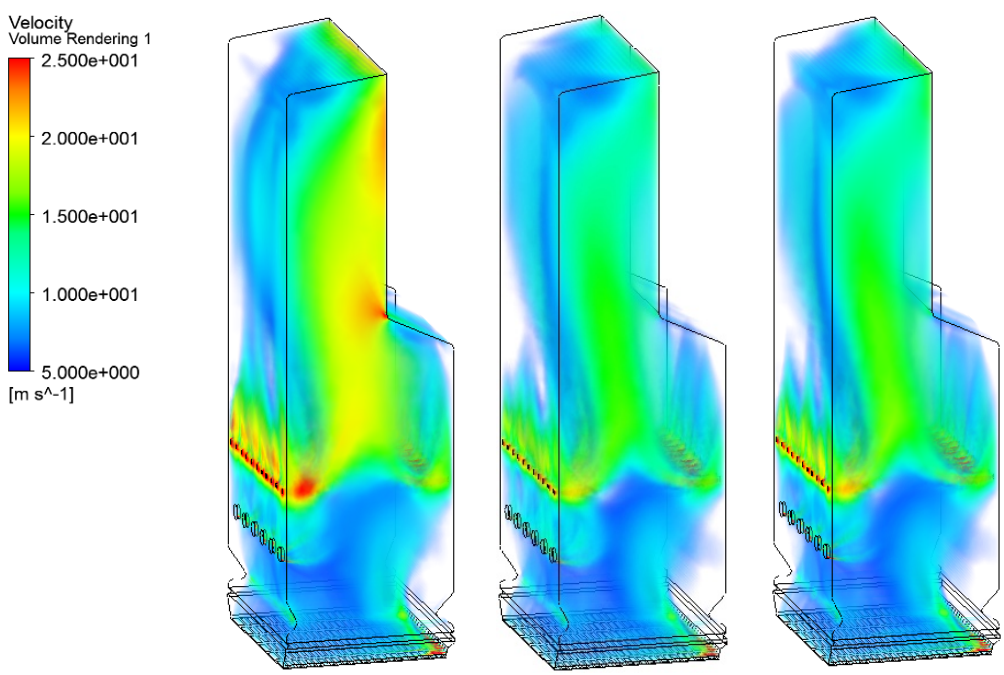
- Combustion without radiation;
- Combustion considering radiation represented by the P1 approximation;
- Combustion considering radiation represented by DTM.

The boiler simulation using the method of the P_1 approximation can provide isotropic scattering of the radiative intensity with its standard parameters. The DTM simulations consider isotropic scattering in this formulation and it was tested for cases of 8, 10, 12 16 and 32 ray tracing directions.

RESULTS

The tests involving the number of ray directions (8, 10, 12, 16 and 32) and radiation intensity in DTM provided identical velocity and temperature profiles. Only the simulation using 32 ray tracing directions required a significant increase in processing time, so the DTM profiles presented in this work are from simulations using 16 ray tracing directions.

Since gradients of temperature intensify turbulence edges, the flue gas flow inside the furnace should be affected by the presence of radiation. Figure 2 compares the volume rendering of flue gas velocity for the three simulated cases.



(a) Without radiation (b) P_1 approximation (c) DTM

Figure 2: Volume rendering of velocity for the simulation cases: (a) without radiation and with radiation represented by (b) the P1 approximation and (c) DTM.

According to Figure 2, the volume renderings applied to the velocity profiles obtained by both methodologies of radiation representation do not show significant differences. However, the presence of radiation in the comprehensive model has great influence on the flue gas flow. This happens due to the fact that radiation provides more energy distribution inside the furnace at high temperatures and allows all element cells to exchange influence with each other. In the absence of radiation, the energy flux can concentrate where it is observed as a preferential ascendant flow. It is expected that convection should be the dominant heat transfer mechanism inside a boiler at high temperatures without radiation. The heat transfer by conduction is limited to exchange of energy in the thermal boundary layer near the boiler walls. Figure 3 presents the vertical temperature profiles in a plane placed in the middle of the bagasse boiler computational domain.

As can be seen in Figure 3, the simulation result for the case without radiation shows high temperatures in the upper furnace and regions where the presence of ascendant preferential flow is expected. This confirms the strong influence of the convection mechanism on the thermal profile. In both of the radiation cases, the results are quite similar, which suggests that, in the temperature range and operational conditions considered, both modeling strategies, the P_1 approximation and DTM, are suitable to represent the radiation heat transfer for heterogeneous combustion of bagasse in a boiler.

The P_1 method does not present any restriction about isotropic emission, scattering or reflection contributions; however, it assumes that the radiation intensity is isotropic or direction independent for a given location in space, over all computational cells of the simulation domain. The DTM only assumes scattering of the isotropic radiation intensity in an optically homogeneous participating media, but the requirement of equally separated paths for ray tracing provides an isotropic character to the model. On the one hand, the P_1 approximation tends to promote a numerical behavior similar to a “second diffusion” because it adds just one more term in the energy conservation equation. On the other hand, DTM is limited to isotropic heat transfer by radiation in a determined number of directions. Even with the conceptual differences and limitations of each radiation strategy representation, both presented similar results and provided a more efficient energy distribution for the case studied in the present work. Moreover, the DTM has two advantages over the P_1 method:

1. It does not insert a “second diffusion” into the conservation equation, which would further increase the numerical instabilities for more detailed simulation cases and,

2. It provides more accurate and flexible control of the representation of radiative heat transfer due to set up of a number of ray path directions.

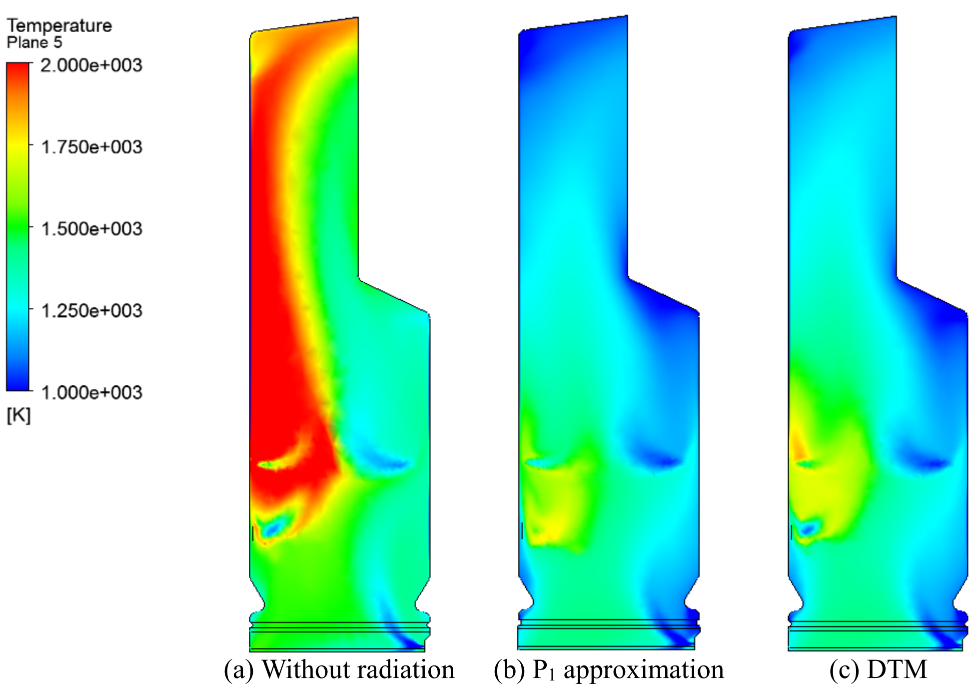


Figure 3: Vertical temperature profiles for the simulation cases: a) without radiation and with radiation represented by b) the P_1 approximation and c) DTM.

CONCLUSIONS

The results showed that heat transfer by radiation should be considered in the CFD combustion simulation of sugarcane bagasse boilers. The radiation model proved to have a great influence on the velocity and temperature profiles. A complete absence of radiation in the model provides incorrect results since the presence of high temperatures in the upper region promoted by an ascendant channel of flue gas flow is incoherent with the interlaced arrangement of the upper secondary air supply ports, the bagasse insertion by swirl burners and the boiler design.

ACKNOWLEDGMENTS

The authors are grateful to the Brazilian agency FAPESP for the grant 2010/50389-3 "*Aplicação da Fluidodinâmica Computacional a uma Caldeira de Bagaço*" and to *Equipalcool Sistemas Ltda*. for the earlier support in the initial prospective work before the FAPESP Grants. Also the authors are grateful to the ESSS technical support team, who offered assistance beyond the tasks of the project.

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